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Measurement of the pp → ZZ production cross section and constraints on anomalous triple gauge couplings in four-lepton final states at $\sqrt{s} = 8$ TeV

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ABSTRACT

A measurement of the inclusive ZZ production cross section and constraints on anomalous triple gauge couplings in proton–proton collisions at $\sqrt{s} = 8$ TeV are presented. The analysis is based on a data sample, corresponding to an integrated luminosity of 19.6 fb^{-1}, collected with the CMS experiment at the LHC. The measurements are performed in the leptonic decay modes $ZZ \to \ell\ell\ell'\ell'$, where $\ell = e, \mu$ and $\ell' = e, \mu, \tau$. The measured total cross section $\sigma(pp \to ZZ) = 7.7 \pm 0.5\ (\text{stat})^{+0.5}_{-0.4}\ (\text{syst}) \pm 0.4\ (\text{theo}) \pm 0.2\ (\text{lumi})$ pb, for both Z bosons produced in the mass range $60 < m_Z < 120$ GeV, is consistent with standard model predictions. Differential cross sections are measured and well described by the theoretical predictions. The invariant mass distribution of the four-lepton system is used to set limits on anomalous ZZZ and ZZγ couplings at the 95% confidence level: $-0.004 < f_4^Z < 0.004$, $-0.004 < f_5^Z < 0.004$, $-0.005 < f_4^\gamma < 0.005$, and $-0.005 < f_5^\gamma < 0.005$.

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1. Introduction

The study of diboson production in proton–proton collisions provides an important test of the electroweak sector of the standard model (SM), especially the non-Abelian structure of the SM Lagrangian. In the SM, ZZ production proceeds mainly through quark–antiquark t- and u-channel scattering diagrams. At high-order calculations in QCD, gluon–gluon fusion also contributes via box diagrams with quark loops. There are no tree-level contributions to ZZ production from triple gauge boson vertices in the SM. Anomalous triple gauge couplings (ATGC) ZZZ and ZZγ are introduced using an effective Lagrangian following Ref. [1]. In this parametrization, two ZZZ and two ZZγ couplings are allowed by electromagnetic gauge invariance and Lorentz invariance for on-shell Z bosons and are parametrized by two CP-violating (f_4^V) and two CP-conserving (f_5^V) parameters, where $V = (Z, \gamma)$. Nonzero ATGC values could be induced by new physics models such as supersymmetry [2].

Previous measurements of the inclusive ZZ cross section by the CMS Collaboration at the LHC were performed in the $ZZ \to \ell\ell\ell'\ell'$ decay channels, where $\ell = e, \mu$ and $\ell' = e, \mu, \tau$, with the data corresponding to an integrated luminosity of 5.1 (5.0) fb^{-1} at $\sqrt{s} = 7(8)$ TeV [3,4]. The measured total cross section, $\sigma(pp \to ZZ)$, is $6.24^{+0.86}_{-0.80}\ (\text{stat})^{+0.41}_{-0.32}\ (\text{syst}) \pm 0.14\ (\text{lumi})$ pb at $\sqrt{s} = 7$ TeV and $8.4 \pm 1.0\ (\text{stat}) \pm 0.7\ (\text{syst}) \pm 0.4\ (\text{lumi})$ pb at $\sqrt{s} = 8$ TeV for both Z bosons in the mass range $60 < m_Z < 120$ GeV. The ATLAS Collaboration measured a total cross section of $6.7 \pm 0.7\ (\text{stat})^{+0.4}_{-0.3}\ (\text{syst}) \pm 0.3\ (\text{lumi})$ pb [5] using $ZZ \to \ell\ell\ell\ell$ and $ZZ \to \ell\ell\nu\nu$ final states with a data sample corresponding to an integrated luminosity of 4.6 fb^{-1} at $\sqrt{s} = 7$ TeV and $66 < m_Z < 116$ GeV. Measurements of the ZZ cross sections performed at the Tevatron are summarized in Refs. [6,7]. All measurements are found to agree with the corresponding SM predictions.

Limits on ZZZ and ZZγ ATGCs were set by CMS using the 7 TeV data sample: $-0.011 < f_4^Z < 0.012$, $-0.012 < f_5^Z < 0.012$, $-0.013 < f_4^\gamma < 0.015$, and $-0.014 < f_5^\gamma < 0.014$ at 95% confidence level (CL) [3]. Similar limits were obtained by ATLAS [5].

In this analysis, which is based on the full 2012 data set and corresponds to an integrated luminosity of 19.6 fb^{-1}, results are presented for the ZZ inclusive and differential cross sections as well as limits for the ZZZ and ZZγ ATGCs. The cross sections are measured for both Z bosons in the mass range $60 < m_Z < 120$ GeV; contributions from virtual photon exchange are included.

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2. The CMS detector and simulation

The CMS detector is described in detail elsewhere [8]; the key components for this analysis are summarized here. The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x–y plane. The magnitude of the transverse momentum is $p_T = \sqrt{p_x^2 + p_y^2}$. A superconducting solenoid is located in the central region of the CMS detector, providing an axial magnetic field of 3.8T parallel to the beam direction. A silicon pixel and strip tracker, a crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter are located within the solenoid and cover the absolute pseudorapidity range $|\eta| < 3.0$, where pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. The ECAL barrel region (EB) covers $|\eta| < 1.479$ and two endcap regions (EE) cover $1.479 < |\eta| < 3.0$. A quartz-fiber Cherenkov calorimeter extends the coverage up to $|\eta| < 5.0$. Gas ionization muon detectors are embedded in the steel flux-return yoke outside the solenoid. A first level of the CMS trigger system, composed of custom hardware processors, is designed to select events of interest in less than 4 μs using information from the calorimeters and muon detectors. A high-level-trigger processor farm reduces the event rate from 100 kHz delivered by the first level trigger to a few hundred hertz.

Several Monte Carlo (MC) event generators are used to simulate the signal and background contributions. The $q\bar{q} \to ZZ$ process is generated at next-to-leading order (NLO) with POWHEG 2.0 [9–11] or at leading-order (LO) with SHERPA [12]. The $gg \to ZZ$ process is simulated with GG2ZZ [13] at LO. Other diboson processes (WZ, $Z\gamma$) and the $Z+$jets samples are generated at LO with MADGRAPH 5 [14]. Events from $t\bar{t}$ production are generated at NLO with POWHEG. The PYTHIA 6.4 [15] package is used for parton showering, hadronization, and the underlying event simulation. The default set of parton distribution functions (PDF) used for LO generators is CTEQ6L [16], whereas CT10 [17] is used for NLO generators. The ZZ yields from simulation are scaled according to the theoretical cross sections calculated with MCFM 6.0 [18] at NLO for $qq \to ZZ$ and at LO for $gg \to ZZ$ with the MSTW2008 PDF [19] with renormalization and factorization scales set to $\mu_R = \mu_F = 91.2$ GeV. The τ-lepton decays are simulated with TAUOLA [20]. For all processes, the detector response is simulated using a detailed description of the CMS detector based on the GEANT4 package [21], and event reconstruction is performed with the same algorithms that are used for data. The simulated samples include multiple interactions per bunch crossing (pileup), such that the pileup distribution matches that of data, with an average value of about 21 interactions per bunch crossing.

3. Event reconstruction

A complete reconstruction of the individual particles emerging from each collision event is obtained via a particle-flow (PF) technique [22,23], which uses the information from all CMS subdetectors to identify and reconstruct individual particles in the collision event. The particles are classified into mutually exclusive categories: charged hadrons, neutral hadrons, photons, muons, and electrons.

Electrons are reconstructed within the geometrical acceptance, $|\eta^e| < 2.5$, and for transverse momentum $p_T^e > 7$ GeV. The reconstruction combines the information from clusters of energy deposits in the ECAL and the trajectory in the tracker [24]. Particle trajectories in the tracker volume are reconstructed using a modeling of the electron energy loss and fitted with a Gaussian sum filter [25]. The contribution of the ECAL energy deposits to the electron transverse momentum measurement and its uncertainty are determined via a multivariate regression approach. Electron identification relies on a multivariate technique that combines observables sensitive to the amount of bremsstrahlung along the electron trajectory, the geometrical and momentum matching between the electron trajectory and associated clusters, as well as shower shape observables.

Muons are reconstructed within $|\eta^\mu| < 2.4$ and for $p_T^\mu > 5$ GeV [26]. The reconstruction combines information from both the silicon tracker and the muon detectors. The PF muons are selected from among the reconstructed muon track candidates by applying requirements on the track components in the muon system and matching with minimum ionizing particle energy deposits in the calorimeters.

For τ leptons, two principal decay modes are distinguished: a leptonic mode, τ_ℓ, with a final state including either an electron or a muon, and a hadronic mode, τ_h, with a final state including hadrons. The PF particles are used to reconstruct τ_h with the "hadron-plus-strip" algorithm [27], which optimizes the reconstruction and identification of specific τ_h decay modes. The π^0 components of the τ_h decays are first reconstructed and then combined with charged hadrons to reconstruct the τ_h decay modes. Cases where τ_h includes three charged hadrons are also included. The missing transverse energy that is associated with neutrinos from τ decays is ignored in the reconstruction. The τ_h candidates in this analysis are required to have $|\eta^{\tau_h}| < 2.3$ and $p_T^{\tau_h} > 20$ GeV.

The isolation of individual electrons or muons is measured relative to their transverse momentum p_T^ℓ, by summing over the transverse momenta of charged hadrons and neutral particles in a cone with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the lepton direction at the interaction vertex:

$$R_{\text{Iso}}^\ell = \Big(\sum p_T^{\text{charged}} + \text{MAX}\Big[0, \sum p_T^{\text{neutral}} + \sum p_T^\gamma - \rho \times A_{\text{eff}}\Big]\Big)/p_T^\ell. \quad (1)$$

The $\sum p_T^{\text{charged}}$ is the scalar sum of the transverse momenta of charged hadrons originating from the primary vertex. The primary vertex is chosen as the vertex with the highest sum of p_T^2 of its constituent tracks. The $\sum p_T^{\text{neutral}}$ and $\sum p_T^\gamma$ are the scalar sums of the transverse momenta for neutral hadrons and photons, respectively. The average transverse-momentum flow density ρ is calculated in each event using a "jet area" [28], where ρ is defined as the median of the $p_T^{\text{jet}}/A_{\text{jet}}$ distribution for all pileup jets in the event. The effective area A_{eff} is the geometric area of the isolation cone times an η-dependent correction factor that accounts for the residual dependence of the isolation on pileup. Electrons and muons are considered isolated if $R_{\text{Iso}}^\ell < 0.4$. Allowing τ leptons in the final state increases the background contamination, therefore tighter isolation requirements are imposed for electrons and muons in $ZZ \to \ell\ell\tau\tau$ decays: $R_{\text{Iso}}^\ell < 0.25$ for $Z \to \tau_\ell^+\tau_\ell^-$, and $R_{\text{Iso}}^e < 0.1$ for $Z \to \tau_e\tau_h$, and $R_{\text{Iso}}^\mu < 0.15$ for $\tau_\mu\tau_h$.

The isolation of the τ_h is calculated as the scalar sum of the transverse momenta of the charged hadrons and neutral particles in a cone of $\Delta R = 0.5$ around the τ_h direction reconstructed at the interaction vertex. The τ_h isolation includes a correction for pileup effects, which is based on the scalar sum of transverse momenta of charged particles not associated with the primary vertex in a cone of $\Delta R = 0.8$ about the τ_h candidate direction (p_T^{PU}). The isolation variable is defined as:

$$I^{\mathrm{PF}} = \Big(\sum p_{\mathrm{T}}^{\mathrm{charged}} + \mathrm{MAX}\Big[0, \sum p_{\mathrm{T}}^{\mathrm{neutral}} + \sum p_{\mathrm{T}}^{\gamma} - f \times p_{\mathrm{T}}^{\mathrm{PU}}\Big]\Big), \quad (2)$$

where the scale factor of $f = 0.0729$, which is used in estimating the contribution to the isolation sum from neutral hadrons and photons, accounts for the difference in the neutral and charged contributions and in the cone sizes. Two standard working points are defined based on the value of the isolation sum corrected for the pileup contribution: $I^{\mathrm{PF}} < 1(8)$ GeV for final states including one (two) τ_{h} candidates.

The electron and muon pairs from Z-boson decays are required to originate from the primary vertex. This is ensured by demanding that the significance of the three-dimensional impact parameter relative to the event vertex, $\mathrm{SIP}_{3\mathrm{D}}$, satisfies $\mathrm{SIP}_{3\mathrm{D}} = |\frac{\mathrm{IP}}{\sigma_{\mathrm{IP}}}| < 4$ for each lepton. The IP is the distance of closest approach of the lepton track to the primary vertex and σ_{IP} is its associated uncertainty.

The combined efficiencies of reconstruction, identification, and isolation of primary electrons or muons are measured in data using a "tag-and-probe" technique [29] applied to an inclusive sample of Z events. The measurements are performed in bins of p_{T}^{ℓ} and $|\eta^{\ell}|$. The efficiency for selecting electrons in the ECAL barrel (endcaps) is about 70% (60%) for $7 < p_{\mathrm{T}}^{\mathrm{e}} < 10$ GeV, 85% (77%) at $p_{\mathrm{T}}^{\mathrm{e}} \simeq 10$ GeV, and 95% (89%) for $p_{\mathrm{T}}^{\mathrm{e}} \geq 20$ GeV. It is about 85% in the transition region between the ECAL barrel and endcaps ($1.44 < |\eta| < 1.57$), averaging over the whole p_{T} range. The muons are reconstructed and identified with an efficiency greater than ~98% in the full $|\eta^{\mu}| < 2.4$ range. The τ_{h} reconstruction efficiency is approximately 50% [27].

Final-state radiation (FSR) may affect the measured four-momentum of the leptons if it is not properly included in the reconstruction. For electrons, a significant portion of the FSR photons is included in the reconstructed energy because of the size of the electromagnetic clusters, but for muons additional treatment of the FSR photons is important. All photons reconstructed within $|\eta^{\mu}| < 2.4$ are considered as possible FSR candidates if they have a transverse momentum $p_{\mathrm{T}}^{\gamma} > 2(4)$ GeV and are found within $\Delta R < 0.07$ ($0.07 < \Delta R < 0.5$) from the closest selected lepton candidate and are isolated. The photon isolation observable $R_{\mathrm{Iso}}^{\gamma}$ is the sum of the transverse momenta of charged hadrons, neutral hadrons, and photons in a cone of $\Delta R = 0.3$ around the candidate photon direction, divided by p_{T}^{γ}. Isolated photons must satisfy $R_{\mathrm{Iso}}^{\gamma} < 1$. The recovered FSR photon is included in the lepton four-momentum and the lepton isolation is then recalculated without it.

The performance of the FSR selection algorithm has been determined using simulated samples, and the rate is verified with the Z and ZZ events in data. The photons within the acceptance for the FSR selection are reconstructed with an efficiency of about 50% and with a mean purity of 80%. The FSR photons are recovered in 0.5(5)% of inclusive Z events with electron (muon) pairs.

4. Event selection

The data sample used in this analysis is selected by the trigger system, which requires the presence of a pair of electrons or muons, or a triplet of electrons. Triggers requiring an electron and a muon are also used. For the double-lepton triggers, the highest p_{T} and the second-highest p_{T} leptons are required to have p_{T} greater than 17 and 8 GeV, respectively, while for the triple-electron trigger the thresholds are 15, 8, and 5 GeV. The trigger efficiency for ZZ events within the acceptance of this analysis is greater than 98%. The use of the triple-electron trigger with a looser p_{T} requirement helps to recover 1–2% of the signal events, while for muons such contribution was found to be negligible.

In selected ZZ events, the Z candidate with the mass closest to the Z-boson mass is denoted Z_1 and the other one, Z_2. The selection is designed to give mutually exclusive sets of signal candidates first selecting ZZ decays to 4e, 4μ, and $2\mathrm{e}2\mu$, in the following denoted $\ell\ell\ell''\ell''$; these events are not considered in $\mathrm{ZZ} \to \ell\ell\tau\tau$ channel. The leptons are identified and isolated as described in Section 3. When building the Z candidates, the FSR photons are kept if $|m_{\ell\ell\gamma} - m_{\mathrm{Z}}| < |m_{\ell\ell} - m_{\mathrm{Z}}|$ and $m_{\ell\ell\gamma} < 100$ GeV. In the following, the presence of the photons in the $\ell\ell\ell''\ell''$ kinematics is implicit. The leptons constituting a Z candidate are required to be the same flavor and to have opposite charges ($\ell^+\ell^-$). The pair is retained if it satisfies $60 < m_{\mathrm{Z}} < 120$ GeV. If more than one Z_2 candidate satisfies all criteria, the ambiguity is resolved by choosing the pair of leptons with the highest scalar sum of p_{T}. Among the four selected leptons forming the Z_1 and the Z_2, at least one should have $p_{\mathrm{T}} > 20$ GeV and another one should have $p_{\mathrm{T}} > 10$ GeV. These p_{T} thresholds ensure that the selected events have leptons with p_{T} values on the high-efficiency plateau for the trigger.

For the $\ell\ell\tau\tau$ final state, events are required to have one $\mathrm{Z}_1 \to \ell^+\ell^-$ candidate with $p_{\mathrm{T}} > 20$ GeV for one of the leptons and $p_{\mathrm{T}} > 10$ GeV for the other lepton, and a $\mathrm{Z}_2 \to \tau^+\tau^-$, with τ decaying into τ_{e}, τ_{μ}, or τ_{h}. The leptons from the τ_{ℓ} decays are required to have $p_{\mathrm{T}}^{\ell} > 10$ GeV. The τ_{h} candidates are required to have $p_{\mathrm{T}}^{\tau_{\mathrm{h}}} > 20$ GeV. The FSR recovery is not applied to the $\ell\ell\tau\tau$ final states, since it does not improve the mass reconstruction. The invariant mass of the reconstructed Z_1 is required to satisfy $60 < m_{\ell\ell} < 120$ GeV, and that of the Z_2 to satisfy $m_{\mathrm{min}} < m_{\tau\tau} < 90$ GeV, where $m_{\mathrm{min}} = 20$ GeV for $\mathrm{Z}_2 \to \tau_{\mathrm{e}}\tau_{\mu}$ final states and 30 GeV for all others.

5. Background estimation

The lepton identification and isolation requirements described in Section 3 significantly suppress all background contributions, and the remnant portion of them arise mainly from the Z and WZ production in association with jets, as well as $\mathrm{t\bar{t}}$. In all these cases, a jet or a non-prompt lepton is misidentified as an isolated e, μ, τ_{h}, τ_{e}, or τ_{μ}. Leptons produced in the decay of Z bosons are referred to as prompt leptons; leptons from e.g. heavy meson decays are non-prompt. The requirements to eliminate non-prompt leptons also remove hadrons that appear to be leptons.

To estimate the expected number of background events in the signal region, control data samples are defined for each lepton flavor combination $\ell'\ell'$. The e and τ_{e}, and μ and τ_{μ} are considered as different flavors, since they originate from different particles.

The control data samples for the background estimate are obtained by selecting events containing Z_1, which passes all selection requirements, and two additional lepton candidates $\ell'\ell'$. The additional lepton pair must have opposite charge and matching flavor ($\mathrm{e}^{\pm}\mathrm{e}^{\mp}, \mu^{\pm}\mu^{\mp}, \tau^{\pm}\tau^{\mp}$). Control data samples enriched with $\mathrm{Z} + \mathrm{X}$ events, where X stands for $\mathrm{b\bar{b}}$, $\mathrm{c\bar{c}}$, gluon, or light quark jets, are obtained by requiring that both additional leptons pass only relaxed identification criteria and are required to be not isolated. By requiring one of the additional leptons to pass the full selection requirements, one obtains data samples enriched with WZ events and significant number of $\mathrm{t\bar{t}}$ events. The expected number of background events in the signal region for each flavor pair is obtained by scaling the number of observed $\mathrm{Z}_1 + \ell'\ell'$ events by the lepton misidentification probability and combining the results for $\mathrm{Z} + \mathrm{X}$ and WZ, $\mathrm{t\bar{t}}$ control regions together. The procedure is identical for all lepton flavors.

The misidentification probability, i.e., the probability for a lepton candidate that passes the relaxed requirements to pass the full selection, is measured separately for each flavor from a sample of $\mathrm{Z}_1 + \ell_{\mathrm{candidate}}$ events with a relaxed identification and no isolation

Table 1
The expected yields of ZZ and background events, as well as their sum ("Total expected") are compared with the observed yields for each decay channel. The statistical and systematic uncertainties are also shown.

Decay channel	Expected ZZ yield	Background	Total expected	Observed
4e	$55.28 \pm 0.25 \pm 7.64$	$2.16 \pm 0.26 \pm 0.88$	$57.44 \pm 0.37 \pm 7.69$	54
4μ	$77.32 \pm 0.29 \pm 10.08$	$1.19 \pm 0.36 \pm 0.48$	$78.51 \pm 0.49 \pm 10.09$	75
$2e2\mu$	$136.09 \pm 0.59 \pm 17.50$	$2.35 \pm 0.34 \pm 0.93$	$138.44 \pm 0.70 \pm 17.52$	148
$ee\tau_h\tau_h$	$2.46 \pm 0.03 \pm 0.32$	$3.46 \pm 0.34 \pm 1.04$	$5.92 \pm 0.36 \pm 1.15$	10
$\mu\mu\tau_h\tau_h$	$2.80 \pm 0.03 \pm 0.34$	$3.89 \pm 0.37 \pm 1.17$	$6.69 \pm 0.39 \pm 1.30$	10
$ee\tau_e\tau_h$	$2.79 \pm 0.03 \pm 0.36$	$3.87 \pm 1.26 \pm 1.16$	$6.66 \pm 1.34 \pm 1.29$	9
$\mu\mu\tau_e\tau_h$	$2.87 \pm 0.03 \pm 0.37$	$1.49 \pm 0.67 \pm 0.60$	$4.36 \pm 0.71 \pm 0.73$	2
$ee\tau_\mu\tau_h$	$3.27 \pm 0.03 \pm 0.42$	$1.47 \pm 0.41 \pm 0.44$	$4.74 \pm 0.43 \pm 0.63$	2
$\mu\mu\tau_\mu\tau_h$	$3.81 \pm 0.03 \pm 0.50$	$1.55 \pm 0.43 \pm 0.46$	$5.36 \pm 0.46 \pm 0.70$	5
$ee\tau_e\tau_\mu$	$2.23 \pm 0.03 \pm 0.29$	$3.04 \pm 1.32 \pm 1.50$	$5.27 \pm 1.40 \pm 1.61$	4
$\mu\mu\tau_e\tau_\mu$	$2.41 \pm 0.03 \pm 0.32$	$0.74 \pm 0.51 \pm 0.37$	$3.15 \pm 0.54 \pm 0.51$	5
Total $\ell\ell\tau\tau$	$22.65 \pm 0.05 \pm 2.94$	$19.51 \pm 2.15 \pm 5.85$	$42.16 \pm 2.28 \pm 6.87$	47

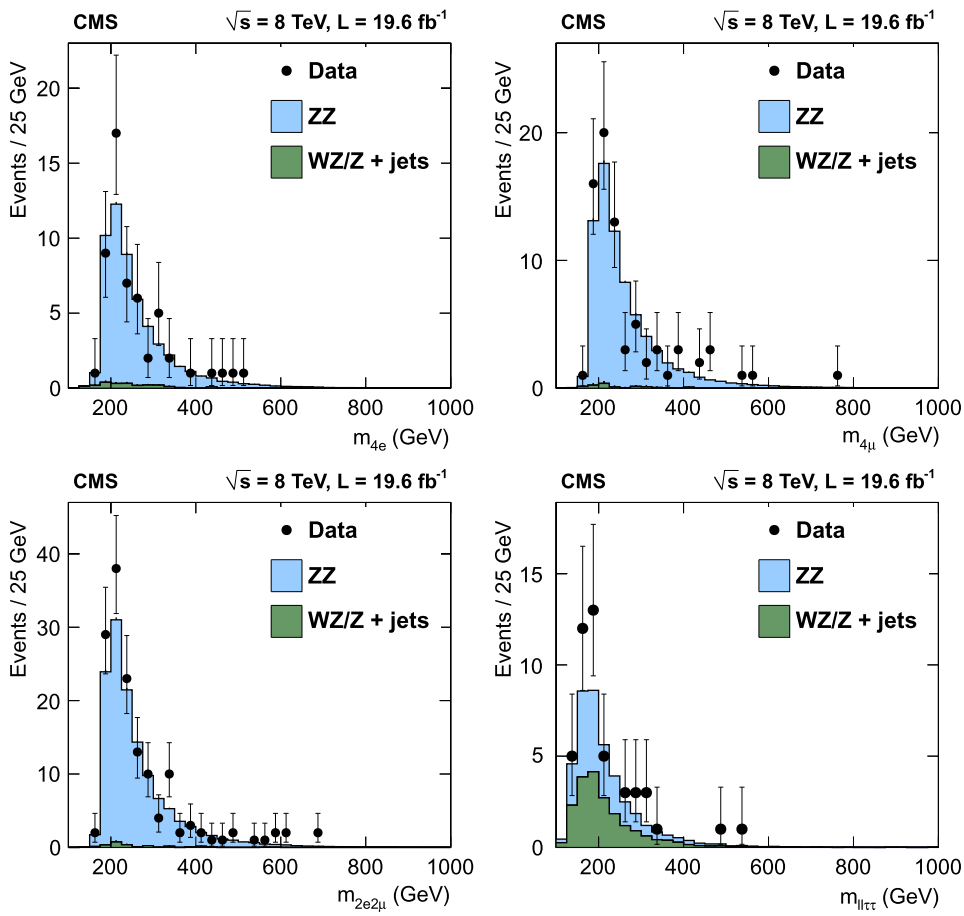

Fig. 1. Distribution of the reconstructed four-lepton mass for the (upper left) 4e, (upper right) 4μ, (lower left) $2e2\mu$, and (lower right) combined $\ell\ell\tau\tau$ decay channels. The data sample corresponds to an integrated luminosity of 19.6 fb^{-1}. Points represent the data, the shaded histograms labeled ZZ represent the POWHEG+GG2ZZ+PYTHIA predictions for ZZ signal, the histograms labeled WZ/Z + jets show the background, which is estimated from data, as described in the text.

requirements on the $\ell_{\text{candidate}}$. The misidentification probability for each lepton flavor is defined as the ratio of the number of leptons that pass the final isolation and identification requirements to the total number of leptons in the sample. It is measured in bins of lepton p_T and η. The contamination from WZ events, which may lead to an overestimate of the misidentification probability because of the presence of genuine isolated leptons, is suppressed by requiring that the measured missing transverse energy is less than 25 GeV.

The estimated background contributions to the signal region are summarized in Table 1. The procedure excludes a possible double counting due to Z + X events that can be found in the WZ control region. A correction for the small contribution of ZZ events in the control region is applied based on MC simulation. The predicted background yield has a small effect on the ZZ cross section measurement in the $\ell\ell\ell''\ell''$ channels, but is comparable to the signal yield for the case of $\ell\ell\tau\tau$.

6. Systematic uncertainties

The systematic uncertainties for trigger efficiency (1.5%) are evaluated from data. The uncertainties arising from lepton identi-

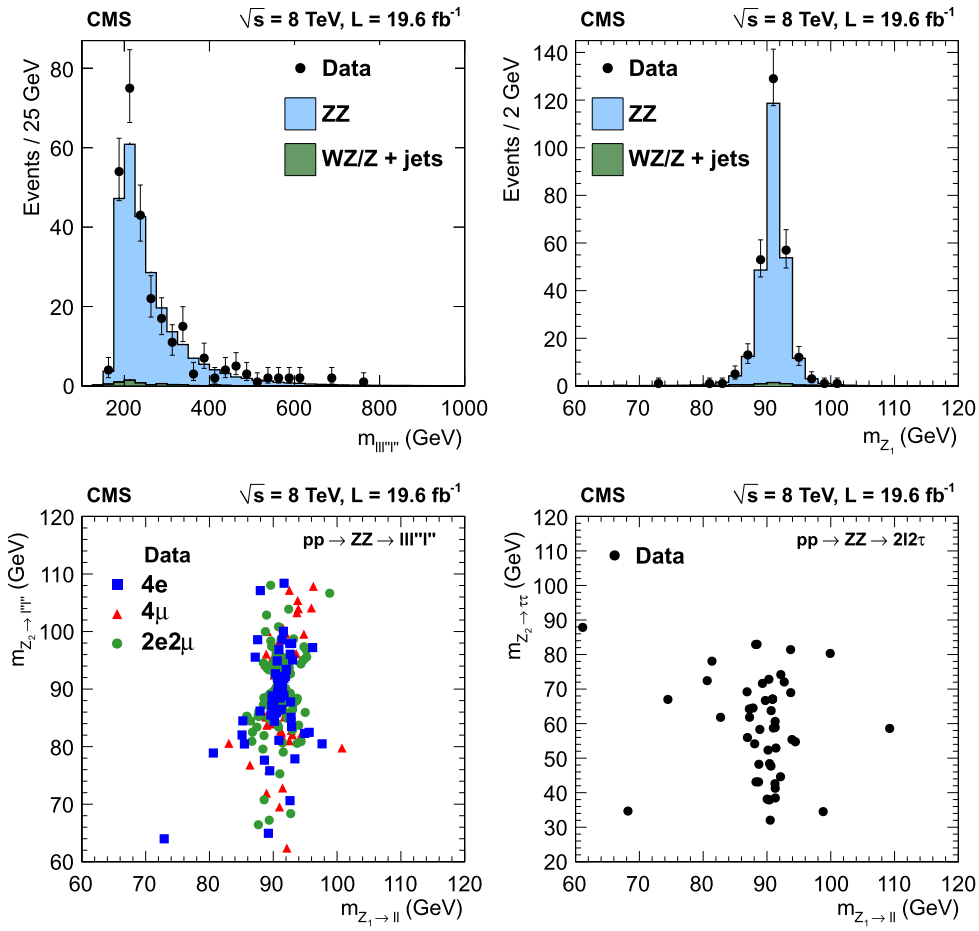

Fig. 2. (upper left) Distribution of the reconstructed four-lepton mass for the sum of the 4e, 4μ, and 2e2μ decay channels. (upper right) Reconstructed Z_1 mass. The correlation between the reconstructed Z_1 and Z_2 masses for the (lower left) combined 4e, 4μ, and 2e2μ final states and (lower right) for $\ell\ell\tau\tau$ final states. Points represent the data, the shaded histograms labeled ZZ represent the POWHEG+GG2ZZ+PYTHIA predictions for ZZ signal, the histograms labeled WZ/Z + jets show background, which is estimated from data, as described in the text.

fication and isolation are 1–2% for muons and electrons, and 6–7% for τ_h. The uncertainty in the LHC integrated luminosity of the data sample is 2.6% [30].

Theoretical uncertainties in the $ZZ \to \ell\ell\ell''\ell''$ acceptance are evaluated using MCFM and by varying the renormalization and factorization scales, up and down, by a factor of two with respect to the default values $\mu_R = \mu_F = m_Z$. The variations in the acceptance are 0.1% (NLO $q\bar{q} \to ZZ$) and 0.4% ($gg \to ZZ$), and can be neglected. Uncertainties related to the choice of the PDF and the strong coupling constant α_s are evaluated following the PDF4LHC [31] prescription and using CT10, MSTW08, and NNPDF [32] PDF sets and found to be 4% (NLO $q\bar{q} \to ZZ$) and 5% ($gg \to ZZ$).

The uncertainties in Z + jets, WZ + jets, and $t\bar{t}$ yields reflect the uncertainties in the measured values of the misidentification rates and the limited statistics of the control regions in the data, and vary between 20% and 70%.

The uncertainty in the unfolding procedure discussed in Section 7 arises from differences between SHERPA and POWHEG for the unfolding factors (2–3%), from scale and PDF uncertainties (4–5%), and from experimental uncertainties (4–5%).

7. The ZZ cross section measurement

The measured and expected event yields for all decay channels are summarized in Table 1. The recently discovered Higgs particle with the mass of 125 GeV does not contribute to this analysis as background because of the phase space selection requirements. The reconstructed four-lepton invariant mass distributions for the 4e, 4μ, 2e2μ, and combined $\ell\ell\tau\tau$ decay channels are shown in Fig. 1. The shape of the background is taken from data. The reconstructed four-lepton invariant mass distribution for the combined 4e, 4μ, and 2e2μ channels is shown in Fig. 2 (upper left). Fig. 2 (upper right) presents the invariant mass of the Z_1 candidates. Figs. 2 (lower left) and (lower right) show the correlation between the reconstructed Z_1 and Z_2 masses for (lower left) 4e, 4μ, and 2e2μ and for (lower right) $\ell\ell\tau\tau$ final states. The data are well reproduced by the signal simulation and with background predictions estimated from data.

The measured yields are used to evaluate the total ZZ production cross section. The signal acceptance is evaluated from simulation and corrected for each individual lepton flavor in bins of p_T and η using factors obtained with the "tag-and-probe" technique. The requirements on p_T and η for the particles in the final state reduce the full possible phase space of the $ZZ \to 4\ell$ measurement by a factor within a range of 0.56–0.59 for the 4e, 4μ, and 2e2μ, depending on the final state, and by a factor of 0.18–0.21 for the $\ell\ell\tau\tau$ final states, with respect to all events generated in the mass window $60 < m_{Z_1}, m_{Z_2} < 120$ GeV. The branching fraction for $Z \to \ell'\ell'$ is $(3.3658 \pm 0.0023)\%$ for each lepton flavor [33].

To include all final states in the cross section calculation, a simultaneous fit to the number of observed events in all decay channels is performed. The likelihood is written as a combination of individual channel likelihoods for the signal and background

Table 2
The total ZZ production cross section as measured in each decay channel and for the combination of all channels.

Decay channel	Total cross section, pb
4e	$7.2^{+1.0}_{-0.9}$ (stat) $^{+0.6}_{-0.5}$ (syst) ± 0.4 (theo) ± 0.2 (lumi)
4μ	$7.3^{+0.8}_{-0.8}$ (stat) $^{+0.6}_{-0.5}$ (syst) ± 0.4 (theo) ± 0.2 (lumi)
$2e2\mu$	$8.1^{+0.7}_{-0.6}$ (stat) $^{+0.6}_{-0.5}$ (syst) ± 0.4 (theo) ± 0.2 (lumi)
$\ell\ell\tau\tau$	$7.7^{+2.1}_{-1.9}$ (stat) $^{+2.0}_{-1.8}$ (syst) ± 0.4 (theo) ± 0.2 (lumi)
Combined	7.7 ± 0.5 (stat) $^{+0.5}_{-0.4}$ (syst) ± 0.4 (theo) ± 0.2 (lumi)

hypotheses, with systematical uncertainties used as nuisance parameters in the fit. Each τ-lepton decay mode, listed in Table 1, is treated as a separate channel.

Table 2 lists the total cross section obtained from each individual decay channel as well as the total cross section based on the combination of all channels. The measured cross section agrees with the theoretical value of 7.7 ± 0.6 pb calculated with MCFM 6.0. In this calculation, the contribution from $q\bar{q} \to ZZ$ is obtained at NLO, while the smaller contribution (approximately 6%) from $gg \to ZZ$ is obtained at LO. The MSTW2008 PDF is used and the renormalization and factorization scales set to $\mu_R = \mu_F = 91.2$ GeV.

The measurement of the differential cross sections is an important part of this analysis, since it provides detailed information about ZZ kinematics. Three decay channels, 4e, 4μ, and $2e2\mu$, are combined, since their kinematic distributions are the same; the $\ell\ell\tau\tau$ channel is not included. The observed yields are unfolded using the method described in Ref. [34].

The differential distributions normalized to the fiducial cross sections are presented in Figs. 3 and 4 for the combination of the 4e, 4μ, and $2e2\mu$ decay channels. The fiducial cross section definition includes p_T^ℓ and $|\eta^\ell|$ selections on each lepton, and the 60–120 GeV mass requirement, as described in Section 4. Fig. 3 shows the differential cross sections in bins of p_T for: (upper left) the highest-p_T lepton in the event, (upper right) the Z_1, and (lower left) the ZZ system. Fig. 3 (lower left) shows the normalized $d\sigma/dm_{ZZ}$ distribution. The data are corrected for background contributions and compared with the theoretical predictions from

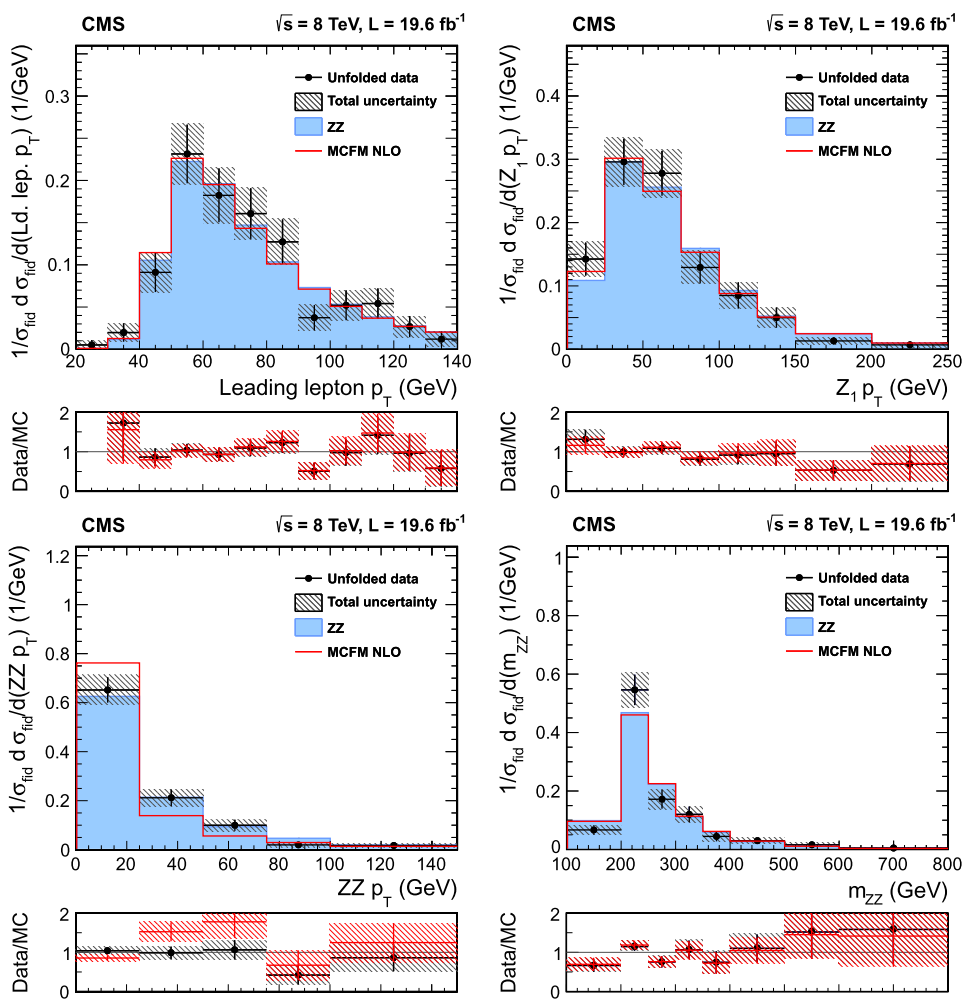

Fig. 3. Differential cross sections normalized to the fiducial cross section for the combined 4e, 4μ, and $2e2\mu$ decay channels as a function of p_T for (upper left) the highest p_T lepton in the event, (upper right) the Z_1, and (lower left) the ZZ system. Figure (lower right) shows the normalized $d\sigma/dm_{ZZ}$ distribution. Points represent the data, and the shaded histograms labeled ZZ represent the POWHEG+GG2ZZ+PYTHIA predictions for ZZ signal, while the solid curves correspond to results of the MCFM calculations. The bottom part of each subfigure represents the ratio of the measured cross section to the expected one from POWHEG+GG2ZZ+PYTHIA (black crosses with solid symbols) and MCFM (red crosses). The shaded areas on all the plots represent the full uncertainties calculated as the quadrature sum of the statistical and systematic uncertainties, whereas the crosses represent the statistical uncertainties only. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

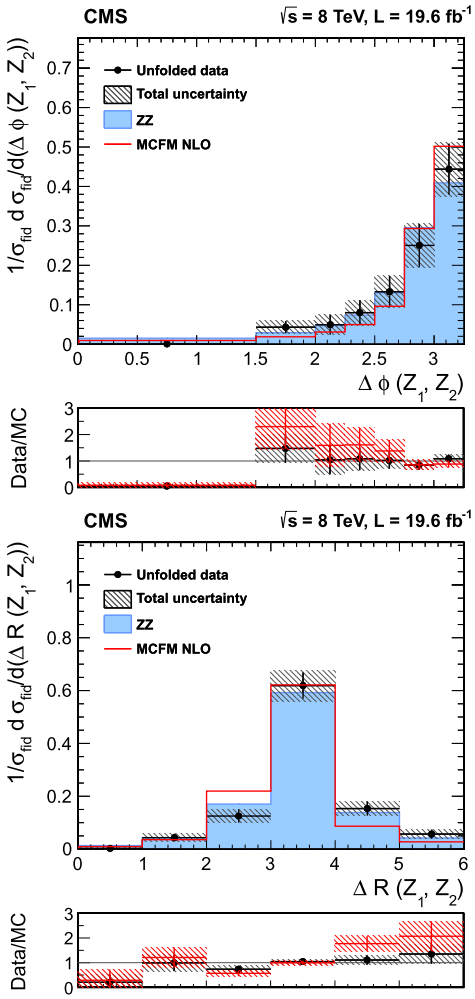

Fig. 4. Differential cross section normalized to the fiducial cross section for the combined 4e, 4μ, and $2e2\mu$ decay channels as a function of (top) azimuthal separation of the two Z bosons and (bottom) ΔR between the Z-bosons. Points represent the data, and the shaded histograms labeled ZZ represent the POWHEG+GG2ZZ+PYTHIA predictions for ZZ signal, while the solid curves correspond to results of the MCFM calculations. The bottom part of each subfigure represents the ratio of the measured cross section to the expected one from POWHEG+GG2ZZ+PYTHIA (black crosses with solid symbols) and MCFM (red crosses). The shaded areas on all the plots represent the full uncertainties calculated as the quadrature sum of the statistical and systematic uncertainties, whereas the crosses represent the statistical uncertainties only. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

POWHEG and MCFM. The bottom part of each plot shows the ratio of the measured to the predicted values. The bin sizes were chosen according to the resolution of the relevant variables, trying also to keep the statistical uncertainties at a similar level for all the bins. Fig. 4 shows the angular correlations between Z bosons, which are in good agreement with the MC simulations. Some difference between POWHEG and MCFM calculations appears at very low p_T of the ZZ system and for azimuthal separation of the Z bosons close to π. This region is better modeled by POWHEG interfaced with the PYTHIA parton shower program.

8. Limits on anomalous triple gauge couplings

The presence of ATGCs would be manifested as an increased yield of events at high four-lepton masses. Fig. 5 presents the distribution of the four-lepton reconstructed mass, which is used to set the limits, for the combined 4e, 4μ, and $2e2\mu$ channels. The shaded histogram represents the results of the POWHEG simulation

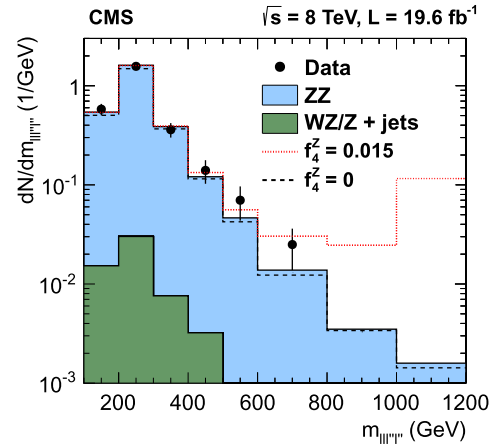

Fig. 5. Distribution of the four-lepton reconstructed mass for the combined 4e, 4μ, and $2e2\mu$ channels. Points represent the data, the shaded histogram labeled ZZ represents the POWHEG+GG2ZZ+PYTHIA predictions for ZZ signal, the histograms labeled WZ/Z + jets shows background, which is estimated from data, as described in the text. The dashed and dotted histograms indicate the results of the SHERPA simulation for the SM ($f_4^Z = 0$) and in the presence of an ATGC ($f_4^Z = 0.015$) with all the other anomalous couplings set to zero. The last bin includes all entries with masses above 1000 GeV.

for the ZZ signal, and the dashed line, which agrees well with it, is the prediction of SHERPA for $f_4^Z = 0$ normalized to the MCFM cross section. The dotted line indicates the SHERPA predictions for a specific ATGC value ($f_4^Z = 0.015$) with all the other anomalous couplings set to zero.

The invariant mass distributions are interpolated from the SHERPA simulation for different values of the anomalous couplings in the range between 0 and 0.015. For each distribution, only one or two couplings are varied while all others are set to zero. The measured signal is obtained from a comparison of the data to a grid of ATGC models in the (f_4^Z, f_4^γ) and (f_5^Z, f_5^γ) parameter planes. Expected signal values are interpolated between the 2D grid points using a second-degree polynomial, since the cross section for signal depends quadratically on the coupling parameters. A profile likelihood method [33] is used to derive the limits. Systematic uncertainties are taken into account by varying the number of expected signal and background events within their uncertainties. No form factor is used when deriving the limits so that the results do not depend on any assumed energy scale characterizing new physics. The constraints on anomalous couplings are displayed in Fig. 6. The curves indicate 68% and 95% confidence levels, and the solid dot shows where the likelihood reaches its maximum. Coupling values outside the contours are excluded at the corresponding confidence levels. The limits are dominated by statistical uncertainties.

One-dimensional 95% CL limits for the $f_4^{Z,\gamma}$ and $f_5^{Z,\gamma}$ anomalous coupling parameters are:

$$-0.004 < f_4^Z < 0.004,$$

$$-0.004 < f_5^Z < 0.004,$$

$$-0.005 < f_4^\gamma < 0.005,$$

$$-0.005 < f_5^\gamma < 0.005.$$

In the one-dimensional fits, all of the ATGC parameters except the one under study are set to zero. These values extend previous CMS results on vector boson self-interactions [3] and improve on the previous limits by factors of three to four, they are presented in Fig. 6 as horizontal and vertical lines.

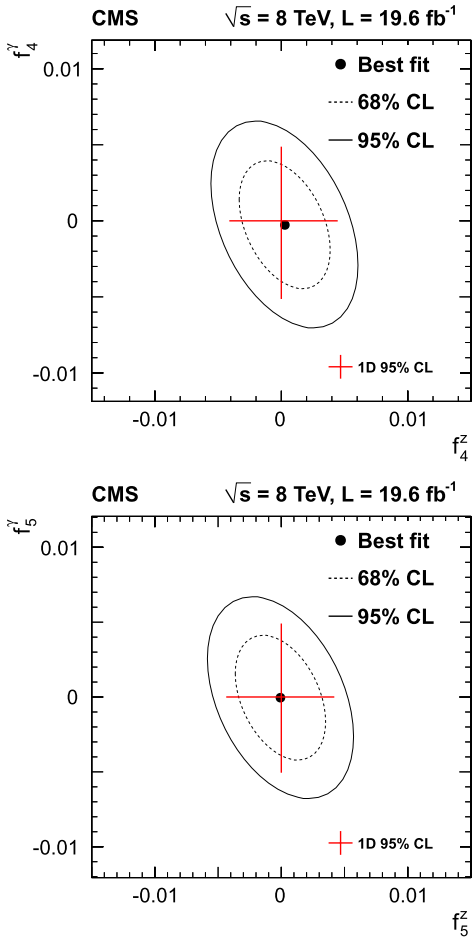

Fig. 6. Two-dimensional exclusion limits at 68% (dashed contour) and 95% (solid contour) CL on the ZZZ and ZZγ ATGCs. The top (bottom) plot shows the exclusion contour in the $(f^Z_{4(5)}, f^\gamma_{4(5)})$ parameter planes. The solid dot shows where the likelihood reaches its maximum. The values of couplings outside of contours are excluded at the corresponding confidence level. The lines in the middle represent one-dimensional limits. No form factor is used.

9. Summary

Measurements have been presented of the inclusive ZZ production cross section in proton–proton collisions at 8 TeV in the $ZZ \to \ell\ell\ell'\ell'$ decay mode, with $\ell = e, \mu$ and $\ell' = e, \mu, \tau$. The data sample corresponds to an integrated luminosity of 19.6 fb^{-1}. The measured total cross section $\sigma(pp \to ZZ) = 7.7 \pm 0.5\ (\text{stat})^{+0.5}_{-0.4}\ (\text{syst}) \pm 0.4\ (\text{theo}) \pm 0.2\ (\text{lumi})$ pb for both Z bosons in the mass range $60 < m_Z < 120$ GeV and the differential cross sections agree well with the SM predictions. Improved limits on anomalous ZZZ and ZZγ triple gauge couplings are established, significantly restricting their possible allowed ranges.

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Corrigendum

Corrigendum to "Measurement of the pp → ZZ production cross section and constraints on anomalous triple gauge couplings in four-lepton final states at $\sqrt{s} = 8$ TeV" [Phys. Lett. B 740 (2015) 250]

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An error was found in the published version in the right plot in Fig. 4. The bin-by-bin normalization for data and MC prediction in this plot is incorrect. The corrected figure is shown in Fig. 1. The physics conclusion of the paper remains unchanged.

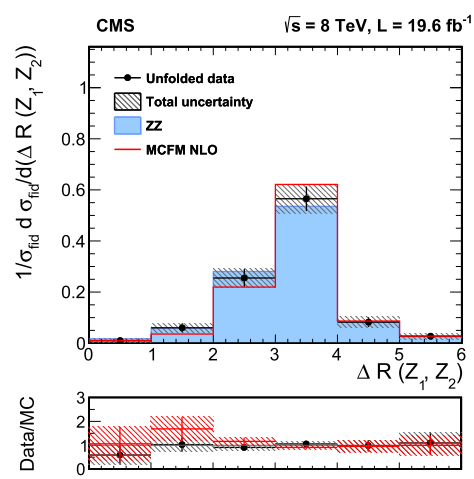

Fig. 1. Differential cross section normalized to the fiducial cross section for the combined 4e, 4μ, and $2e2\mu$ decay channels as a function of ΔR between the Z-bosons. Points represent the data, and the shaded histograms labeled ZZ represent the POWHEG+GG2ZZ+PYTHIA predictions for ZZ signal, while the solid curve corresponds to results of the MCFM calculations. The bottom part represents the ratio of the measured cross section to the expected one from POWHEG+GG2ZZ+PYTHIA (black crosses with solid symbols) and MCFM (red crosses). The shaded areas on all the plots represent the full uncertainties calculated as the quadrature sum of the statistical and systematic uncertainties, whereas the crosses represent the statistical uncertainties only. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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